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(54) Wavelength Filter Integrated Into an Optical Waveguide

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The present invention relates to a wavelength filter integrated into an optical waveguide and to a method for manufacturing same.

Optical fibers are well known and are extensively used in communications, control systems, sensing or medical devices. The advantages that optical fibers possess, for communication purposes, over conventional copper wire conductors and coaxial cables are such that eventually the optical fiber will replace them in many applications for transmission of information signals.

Optical fibers are waveguides that can support visible or infrared light. In order to reduce the dispersion of signals, monomode fibers are used and are now the most promising type of fiber in communications. As waveguides, monomode optical fibers can carry several wavelengths. However, many applications require that only certain specific wavelengths be transmitted by the fiber, requiring a filter to eliminate the undesired wavelengths. Applications such as the wavelength demultiplexing of signals, that is the separation of signals at different wavelengths transmitted in the same fiber may need a wavelength filter, in particular, a narrow passband filter. Such a filter may also be used to lock the

frequency of a laser or of a laser diode, or to construct a frequency amplitude converter.

Optical filters exist but they suffer from many disadvantages such as poor performance, high complexity, high manufacturing costs, etc., and they are not usually an inherent part of the optical transmission media.

Therefore, an object of the present invention is an improved wavelength filter integrated into an optical waveguide.

Another object of the invention is an improved method for manufacturing a wavelength filter integrated into an optical waveguide.

The term "light" as used herein is intended to encompass both visible light as well as light in other parts of the spectrum than visible light which may propagate in the wavelength filter integrated into an optical waveguide, according to this invention.

The wavelength filter integrated into an optical waveguide (hereinafter "wavelength filter"), according to this invention, is fabricated from a monomode optical fiber comprising a core made of light

transmitting material surrounded by a layer of cladding, also made from a light transmitting material. The cladding layer is received in a jacket made typically of opaque plastic material.

The wavelength filter is constituted by a plurality of successive concatenated biconical tapered portions (hereinafter "tapers") along the light path defined by the monomode fiber, and formed at spaced locations thereon.

Each taper is a constriction or narrowing of the monomode optical fiber and comprises three constituent elements, namely an elongated beating region which is connected to the monomode optical fiber by two conical coupling zones. In the beating region, light is essentially guided by the cladding surrounded by air. As opposed to the monomode core-cladding guide, this cladding-air guide is highly multimode. In the conical coupling zones, a power transfer or coupling takes place from the HE_{11} core-mode to the HE_{11} and HE_{12} cladding-modes and vice-versa. In the central quasi-cylindrical region, only beating between these excited cladding-modes occurs. The transmission of the taper depends on the shape and size of the coupling zones and the beating region, thus on the profile of the taper. The profile of the taper is the

the diameter of the monomode optical fiber, in the taper region, as a function of the length.

In combination, the characteristics of the tapers, namely their respective profiles and their number determine the characteristics of the filter.

A taper may be formed on the monomode fiber by heating locally the fiber, by using preferably a flame having a width of 2 mm or less, up to the point at which the fiber becomes viscous and then stretching the fiber by applying a small tension along the central axis thereof. The heat is then removed allowing the fiber to cool.

As an alternative, the tapers may be manufactured independently on short sections of a monomode optical fiber and to construct the wavelength filter, the tapers are joined together, by using a known technique, such as splicing.

It is plain that the two options may be combined and a wavelength filter may be manufactured by integrally forming some of the tapers on a monomode optical fiber and by adding the remaining tapers in the fiber, such as by splicing.

Provided the flame used to manufacture the taper is narrow ($\leq$2 mm), the following relation may be used to approximate the transmitted power of an abrupt taper formed on a monomode optical fiber:

$$t(\lambda) = \cos^2(\pi(\lambda - \lambda_o)/2\Lambda)$$

where:

t is the normalized transmitted power;

λ_o is a reference wavelength at which the taper transmission is maximum;

Λ is the half period of the spectral response of the taper.

The spectral response of the wavelength filter is equal to the product of the spectral responses of each of the tapers. If the transmission of the tapers is chosen to be maximum at the same reference wavelength λ_o, the spectral response of the wavelength filter may be approximated by:

$$T(\lambda) = \prod_{i=1}^{n} \cos^2 (\pi(\lambda - \lambda_o)/2\Lambda i)$$

where:

T is the normalized transmitted power of the wavelength filter;

n is the number of tapers which constitute the filter; and

Λ_i is the half period of the spectral response of the i^{th} taper.

Thus, the characteristics of the wavelength filter, according to the present invention, depend on the number of tapers as well as on the half period Λ of each taper. Λ of one taper depends on the taper profile. During the manufacture of the wavelength filter, one end of a monomode optical fiber is illuminated and the output signal at the opposite end of the fiber is monitored. During the stretching, the output signal oscillates. The present inventors have found that Λ, the half period of the spectral response of a taper is approximately equal to $\frac{\lambda}{2N}$, λ being the wavelength of the light source used to illuminate the monomode fiber, and N being the number of oscillations counted during the stretching of the monomode fiber. Thus, for each taper, the profile which gives the desired Λ may be obtained by counting the number of oscillations during the stretching and

interrupting the tapering process when a predetermined number of oscillations has been reached.

The light source for illuminating the optical monomode fiber during the manufacture of the wavelength filter should preferably emit at the same wavelength at which the wavelength filter is tuned, which is λ_o. In certain cases, however, it may be desirable to use a light source which emits at a different wavelength. This may be achieved by using the $\Lambda = \frac{\lambda}{2N}$ relation to effectively predict the number of oscillations N which would be counted at different wavelengths.

For a mass production of the wavelength filter, according to the present invention, it may very well be envisaged to form each taper on the optical fiber simply by stretching the fiber a predetermined length instead of counting the number of oscillations of a light signal in the fiber. This method would be well suited for a highly automated production and may be used only if the characteristics of the manufacturing setup (i.e. the flame size, temperature, etc.) are reproducible with precision.

Therefore, the present invention comprises in a most general aspect a wavelength filter integrated

into an optical waveguide, the wavelength filter having a predetermined filtering characteristic, the optical waveguide being constituted by a fiber of light propagating material defining a light path, the wavelength filter comprising a plurality of successive concatenated biconical tapered portions on the fiber along the light path, each biconical tapered portion being formed on a length of a monomode optical fiber, the biconical tapered portions having different profiles such as to produce the desired filtering characteristic.

This invention further encompasses a method for manufacturing a wavelength filter integrated into an optical waveguide, the wavelength filter having a predetermined filtering characteristic, the method comprising the step of forming a succession of concatenated biconical tapered portions, the succession of biconical tapered portions constituting an optical waveguide defining a light path, each biconical tapered portion being formed on a section of a monomode optical fiber by heating locally and controllably stretching the section of a monomode optical fiber to form a biconical tapered portion having a certain profile, the biconical tapered portions having different profiles such as to produce the predetermined filtering characteristic of the wavelength filter.

Preferred embodiments of the present invention will now be described with reference to the annexed drawings in which:

Figure 1 is a perspective view of a commercially available monomode optical fiber;

Figure 2 is a perspective view of a monomode optical fiber on which a taper has been formed;

Figure 3 is a diagram illustrating the transmitted power of a taper as a function of elongation;

Figure 4:

a) is a diagram illustrating the transmitted power through a taper as a function of the wavelength;

b) is the normalization curve of the system;

Figure 5 is an experimental plot of the inverse half period in the spectral response of a taper versus N the number of power oscillations counted during the elongation of the taper;

Figure 6 is a diagram illustrating the

theoretical response of a wavelength filter with four tapers;

Figure 7 is a schematical view of a setup for manufacturing a wavelength filter, according to the present invention;

Figure 8:

a) is a diagram of the spectral response of the wavelength filter shown in Figure 7;

b) is the normalization curve of the system; and

Figure 9 is a theoretical diagram of the inverse half-period in the spectral response of a taper, with respect to N, the number of power oscillations counted during the stretching of the taper, at two different wavelengths.

The monomode optical fiber 10 illustrated in Figure 1 comprises a core 12 made of transparent material such as germanium dopped silica, surrounded by a cladding layer 14 made of transparent material such as pure silica. A jacket 16 of opaque plastic material is mounted on cladding layer 14 and acts as a cladding-mode stripper.

Optical fiber 10 is well known in the art and is commonly used in communications and control systems. As an example, Newport Corporation supplies such fibers which, typically, have a core and a cladding diameters of 3.6 µm and 127 µm respectively, and a second mode cut off wavelength of 578 nm.

The wavelength filter, according to the present invention, is fabricated from the monomode optical fiber 10 by forming on the fiber 10, or by serially connecting a plurality of successive tapers. Figure 2 illustrates a taper 18 which comprises a thin and approximately cylindrical beating zone 21 connected to the fiber 10 by two conical coupling zones 19 which taper toward the beating zone 21.

The taper 18 modifies the light signal passing through monomode fiber 10, and a plurality of such tapers will perform the function of a wavelength filter. By changing the profile of the tapers, as well as the number of tapers on the fiber 10, the characteristics of the wavelength filter may be controlled.

The taper 18 is constructed by heating locally the fiber 10 up to the point at which it becomes viscous and, by stretching the fiber along its

axis. As a heat source, it is preferable to use a narrow flame, however, it may be envisaged to use other heat sources.

The variations of the transmitted power or the spectral response of a light signal in monomode fiber 10, during the tapering, is illustrated in the diagram of Figure 3. N, which is the number of oscillations counted during the stretching process can be easily determined from the power versus elongation diagram.

Provided the flame used to manufacture the taper is narrow ($\leqslant 2$ mm), one can obtain the wavelength response illustrated in Figure 4. Figure 4a illustrates the response of the taper 18 with respect to λ, the wavelength of the electromagnetic excitation. Figure 4b is the normalization curve of the system. It may be observed that the response of taper 18 is not exactly sinusoidal which is due to a perturbation, indicating the presence of a third mode (HE_{13}) in the taper 18.

By neglecting the perturbation effect, the following relation may be used to approximate the spectral response of an abrupt taper, to an electromagnetic radiation having a wavelength λ :

$$t(\lambda) = \cos^2 (\pi(\lambda-\lambda_o)/2\Lambda)$$

where:

t is the transmitted power of the taper;

λ_o is a reference wavelength at which the taper transmission is maximum;

Λ is the half period of the oscillation which occurs in the beating region 21 of taper 18.

The inverse half period of the wavelength response is approximately a linear function of N, the number of oscillations encountered while tapering the fiber, as can be seen in Figure 5. Thus, the period of the spectral response decreases as N increases, that is as the elongation increases.

The spectral response of a series of concatenated tapers on fiber 10 is equal to the product of the spectral responses of each of the tapers. If the transmission of the tapers are chosen to be maximum at the same reference wavelength λ_o, the spectral response of the series of concatenated tapers may be approximated by:

$$T(\lambda) = \prod_{i=1}^{n} \cos^2(\pi(\lambda-\lambda_o)/2\Lambda_i)$$

where:

T is the transmitted power of the i^{th} taper;

Λ_i is the half period of the oscillation which occurs in the beating region of the i^{th} taper; and

n is the number of tapers of the wavelength filter.

Choosing $\Lambda_i=2^{i-1}\Lambda_1$ gives a series that when n tends to infinity, is equal to $\mathrm{sinc}^2\{\pi(\lambda-\lambda_o)/\Lambda_1\}$ which represents a narrow band filter centered on λ_o with a half-power width $\delta\lambda$ which is proportional to $\Lambda_1 (\delta\lambda \approx 0.89\Lambda_1)$ which is the smallest Λ in the series. Since $1/\Lambda$ is proportional to N, the series can be obtained with $N_i=(1/2)^{i-1}N_1$, the width of the filter being determined by N_1 which corresponds to the taper with the greatest number of oscillations.

Practically, the choice of N_1 is limited by N_{max} which is the number of oscillations recorded during the stretching of the fiber 10 before the taper

breaks. Since the series cannot be infinite, the spectrum will exhibit periodic peaks, the distance between the peaks depending on the taper with the largest spectrum period, in other words, the smallest N.

The theoretical spectral response of a wavelength filter with four tapers, is shown on the diagram of Figure 6. Each of the periodic peaks A, B and C, respectively, has a half power width of 0.89Λ_1 and the wavelength filter may be assimilated to a passband filter over a bandwith which includes only one of the peaks. For example, for applications were the operating bandwith is restricted between the peaks A and C, the filter will perform as a bandpass filter, eliminating, or strongly attenuating all the frequencies in the operating bandwith except a narrow band centered on λo.

Referring to Figure 7, a wavelength filter 23 is constructed by forming on an optical monomode fiber 10 four consecutive tapers, as follows. A white light source 20 is coupled at one end of fiber 10 and the opposite end of the fiber is placed in the entry slot of a grating monochromator 22, known in the art, and equipped with a photomultiplier. The wavelength of the filter, in other words, the wavelength which will be

the least attenuated by the filter is selected arbitrarily at 766 nm.

To achieve a good selectivity, the number of tapers is established to four. The taper with the greatest number of oscillations, designated N_1 is fixed at 32.

By using $N_1 = 32$, the formula

$$N_i=(1/2)^{i-1}N_1 \text{ gives}$$

$N_2 = 16$

$N_3 = 8$

$N_4 = 4$

The jacket of the optical fiber is stripped at the location where the first taper is to be formed. The fiber 10 is then heated locally by using a narrow flame, having preferably a width of 2 mm or less, to a temperature up to its softening point and it is stretched while monitoring the output signal by the monochromator. When the number of oscillations reaches 32, the stretching is interrupted and the fiber is allowed to cool. The same steps are followed for forming the three other tapers on the fiber except that the number of oscillations is different for each taper.

Alternatively, the wavelength filter 23 may

be contructed by forming each of the tapers independently, on a short section of a monomode fiber and by joining the tapers serially.

It is plain that both options may be combined and the wavelength filter, according to this invention, may also be constructed by forming some of the tapers of the filter directly on the monomode optical fiber, while adding the remaining tapers in the monomode optical fiber, such as by splicing.

In order to obtain a good performance of the wavelength filter, according to the present invention, it is necessary to provide a cladding-mode stripper at each end of each taper on the optical fiber. As an example, a suitable cladding-mode stripper may be obtained by leaving the jacket of the fiber at such locations.

Figure 8 illustrates the response of the wavelength filter 23. The expected 766 nm peak is present and has a width of 5.8 nm with a transmission of 50%. The power losses are due to the inherent loss of each taper and to the difficulty of controlling precisely the stretching process, in other words, stopping exactly on a maximum in the transmitted power. The perturbation due to the presence of a third mode can also contribute to losses in each taper up to 15%.

It might be observed that throughout the studied range (300 nm) there is an almost total extinction of all the non-desired peaks, even the one predicted by the model (corresponding to 598 nm) The residual peaks can always be suppressed by adding the appropriate taper (which is not necessarily in the series ex: adding a taper with N= 24 reduces the side lobes). To broaden the range of utility of the filter, it is always possible to bend the fiber to eliminate the transmission of greater wavelengths.

The above described method for manufacturing wavelength filters necessitates a light source emitting at a wavelength at which the filter is to be tuned. This may be a disadvantage in certain cases and it may be desirable to use a light source emitting at a certain wavelength to manufacture a large variety of filters tuned at different wavelengths.

For example, one might want to construct a wavelength filter at λ_F = 900 nm which requires that the longest taper be of a period Λ = 12 nm. If only a HeNe (Helium/Neon) laser is available which emits at λ_L = 633 nm, the following reasoning may be followed.

Since, as stated earlier

$$\Lambda = \frac{\lambda}{2N},$$

the number of oscillations N_F which are necessary to obtain Λ = 12 nm, when the stretching of the taper is performed when the optical fiber is illuminated with a light source at λ_F = 900 nm, is:

$$N_F = \frac{\lambda_F}{2\Lambda} = \frac{900}{24} = 37,5.$$

To obtain a maximum in the transmission at λ_F, N_F must be an integer. Therefore, the closest value to choose for N_F in order to obtain a maximum in the transmission at λ_F = 900 nm is 37 or 38.

By choosing arbitrarily 37, one will have

$$\Lambda' = \frac{\lambda_F}{2N_F} = \frac{900}{2 \times 37} = 12.16 \text{ nm}.$$

The value for N_L, the number of oscillations to be counted during the stretching of the taper while it is illuminated with the laser emitting at 633, nm may then be determined:

$$N_L = \frac{\lambda_L}{2\Lambda'} = \frac{633}{2x12,16} = 26,03.$$

By interrupting the stretching after 26.03 oscillations, a transmission having a maximum at 900 nm will be obtained with a $\Lambda' = 12.16$ nm.

Figure 9 illustrates the relation between Λ^{-1} and N, for two wavelengths $\lambda = 633$ nm and $\lambda = 900$ nm, respectively. At each wavelength, there is a linear relation between Λ^{-1} and N, more specifically, $\Lambda^{-1} = \frac{2N}{\lambda}$.

The other tapers of the filter may then be constructed, using the $N_i = 1/2^{i-1}N_1$ series, but with $N_1 = 26{,}03$.

For a mass production of the wavelength filter, according to the present invention, it may very well be envisaged to produce each taper by stretching the optical fiber a predetermined length, instead of counting for each taper the number of oscillations of a light signal in the fiber. This method, well suited for a highly automated production would require a device that can elongate the optical fiber with precision, and has an important advantage in that it obviates the use of an equipment to monitor the light signal in the fiber. However, it should be observed that the heat source, used to soften the fiber prior the stretching, must have highly reproducible

characteristics, such as the flame size, temperature etc., in order to produce tapers having identical responses from one production run to another. Generally speaking, if the manufacturing setup would have non reproducible characteristics, tapers having the same length, may not have the same response.

It should be understood that the scope of the present invention is not intended to be limited to the specific preferred embodiments illustrated in the drawings and described above.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A wavelength filter integrated into an optical waveguide, said wavelength filter having a predetermined filtering characteristic, said optical waveguide being constituted by a fiber of light propagating material defining a light path, said wavelength filter comprising a plurality of successive concatenated biconical tapered portions on said fiber along said light path, each biconical tapered portion being formed on a length of a monomode optical fiber, said biconical tapered portions having different profiles such as to produce the desired filtering characteristic.

2. A wavelength filter integrated into an optical waveguide as defined in claim 1, wherein a plurality of the biconical tapered portions of said wavelength filter are integrally formed on a length of a monomode optical fiber.

3. A wavelength filter integrated into an optical waveguide as defined in claim 1, wherein each biconical tapered portion is formed on an individual

section of a monomode optical fiber, the individual sections being operatively connected to each other to form said wavelength filter.

4. A wavelength filter integrated into an optical waveguide as defined in claim 2, wherein at least one of the biconical tapered portions of said wavelength filter is formed on an individual section of a monomode optical fiber, said section being operatively connected to said length of a monomode optical fiber.

5. A wavelength filter integrated into an optical waveguide as defined in claim 1, wherein the biconical tapered portions are formed by heating a monomode optical fiber with a flame having a width less than 2 mm up to the softening point of said monomode optical fiber and by stretching said monomode optical fiber.

6. A wavelength filter integrated into an optical waveguide as defined in claim 5, wherein the transmitted power of a given biconical tapered portion is approximately:

$$t(\lambda) = \cos^2(\pi(\lambda - \lambda_o)/2\Lambda)$$

wherein:

- t is the normalized transmitted power of the biconical tapered portion along said light path;

- λ is the wavelength of the light passing through said filter;

- λ_o is a reference wavelength at which the transmission of said given biconical tapered portion is maximum; and

- Λ is the half-period of the spectral response of the said given biconical tapered portion.

7. A wavelength filter integrated into an optical waveguide as defined in claim 6, wherein the spectral response of said filter is approximately:

$$T(\lambda) = \prod_{i=1}^{n} \cos^2(\pi(\lambda - \lambda_o)/2\Lambda i)$$

wherein:

T is the normalized transmitted power of said filter;

Λ_i is the half-period of the spectral response of the i^{th} biconical tapered portion of said filter; and

n is the number of biconical tapered portions of said filter.

8. A wavelength filter integrated into an optical waveguide as defined in claims 1, 2 or 3, wherein said filter comprises four biconical tapered portions.

9. A wavelength filter, as defined in claim 1, wherein said optical waveguide comprises cladding-mode stripper means.

10. A wavelength filter, as defined in claim 9, wherein said cladding-mode stripper means include jacket means at each end of each biconical tapered portion.

11. A method for manufacturing a wavelength filter integrated into an optical waveguide, said wavelength filter having a predetermined filtering characteristic, said method comprising the step of forming a succession of concatenated biconical tapered portions, said succession of biconical tapered portions

constituting an optical waveguide defining a light path, each biconical tapered portion being formed on a section of a monomode optical fiber by heating locally and controllably stretching said section of a monomode optical fiber to form a biconical tapered portion having a certain profile, the biconical tapered portions having different profiles such as to produce the predetermined filtering characteristic of said wavelength filter.

12. A method as defined in claim 11 wherein a plurality of biconical tapered portions of said wavelength filter are formed integrally on a length of a monomode optical fiber.

13. A method as defined in claim 11 wherein each biconical tapered portion is formed on an individual section of a monomode optical fiber, then the individual sections being operatively connected to each other to form said wavelength filter and said optical waveguide.

14. A method as defined in claim 12, wherein at least one biconical tapered portion of said wavelength filter is formed on an individual section of a monomode optical fiber, said individual section being operatively connected to said length of a monomode

optical fiber.

15. A method as defined in claim 11, further comprising the steps of:

- illuminating one end of said section of a monomode optical fiber when said section is heated and stretched; and

- monitoring the output light signal at an opposite end of said section during the stretching thereof, said output light signal being of oscillatory nature during the stretching of said section.

16. A method as defined in claim 15, wherein during the stretching of said section the oscillations of said output light signal being counted.

17. A method as defined in claim 16, wherein the stretching of said section is interrupted when a predetermined number of oscillations has been reached.

18. A method as defined in claim 11, wherein a biconical tapered portion of said wavelength filter is formed by stretching a section of a monomode optical fiber a predetermined length.

19. A method as defined in claim 16 wherein the

number of oscillations for the i^{th} biconical tapered portion of said wavelength filter is determined from the relation:

$$N_i = (1/2)^{i-1} N_1$$

wherein N_1 is the number of oscillations corresponding to the longest biconical tapered portion of said wavelength filter.

20. A method as defined in claim 15, wherein said filter is tuned at a certain wavelength, said section being illuminated with a light source emitting at said certain wavelength.

21. A method as defined in claim 15, wherein said filter is tuned at a certain wavelength, said section being illuminated with a light source emitting at a different wavelength.

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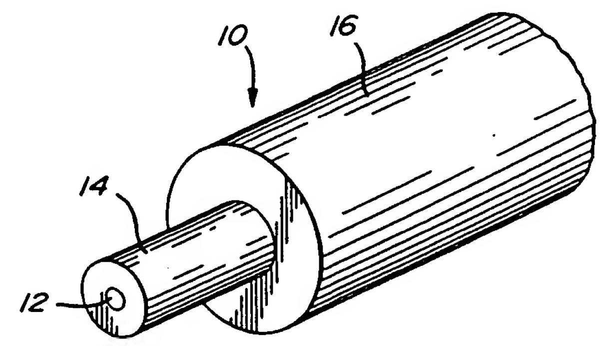

FIG. 1 PRIOR ART

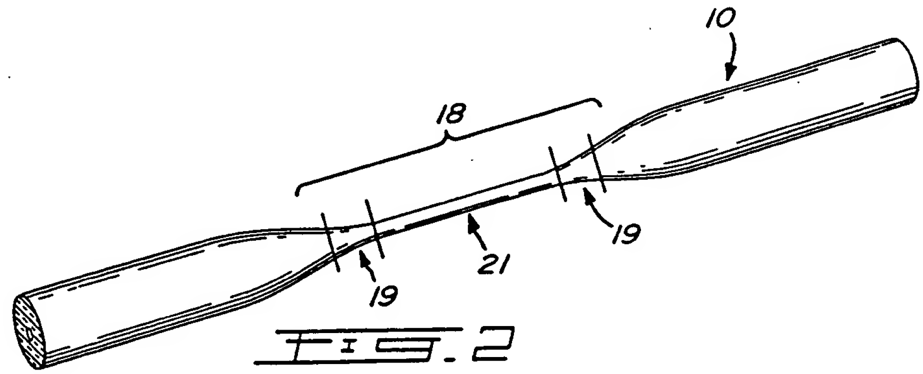

FIG. 2

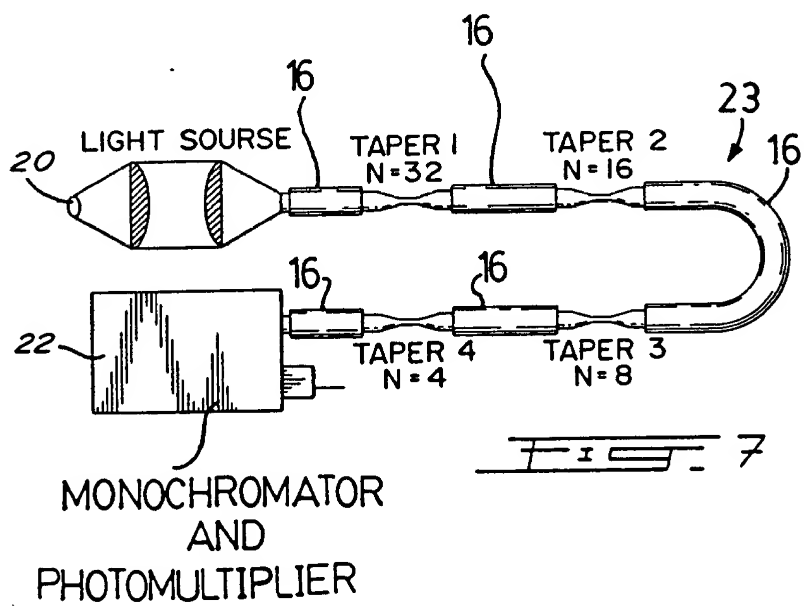

FIG. 7

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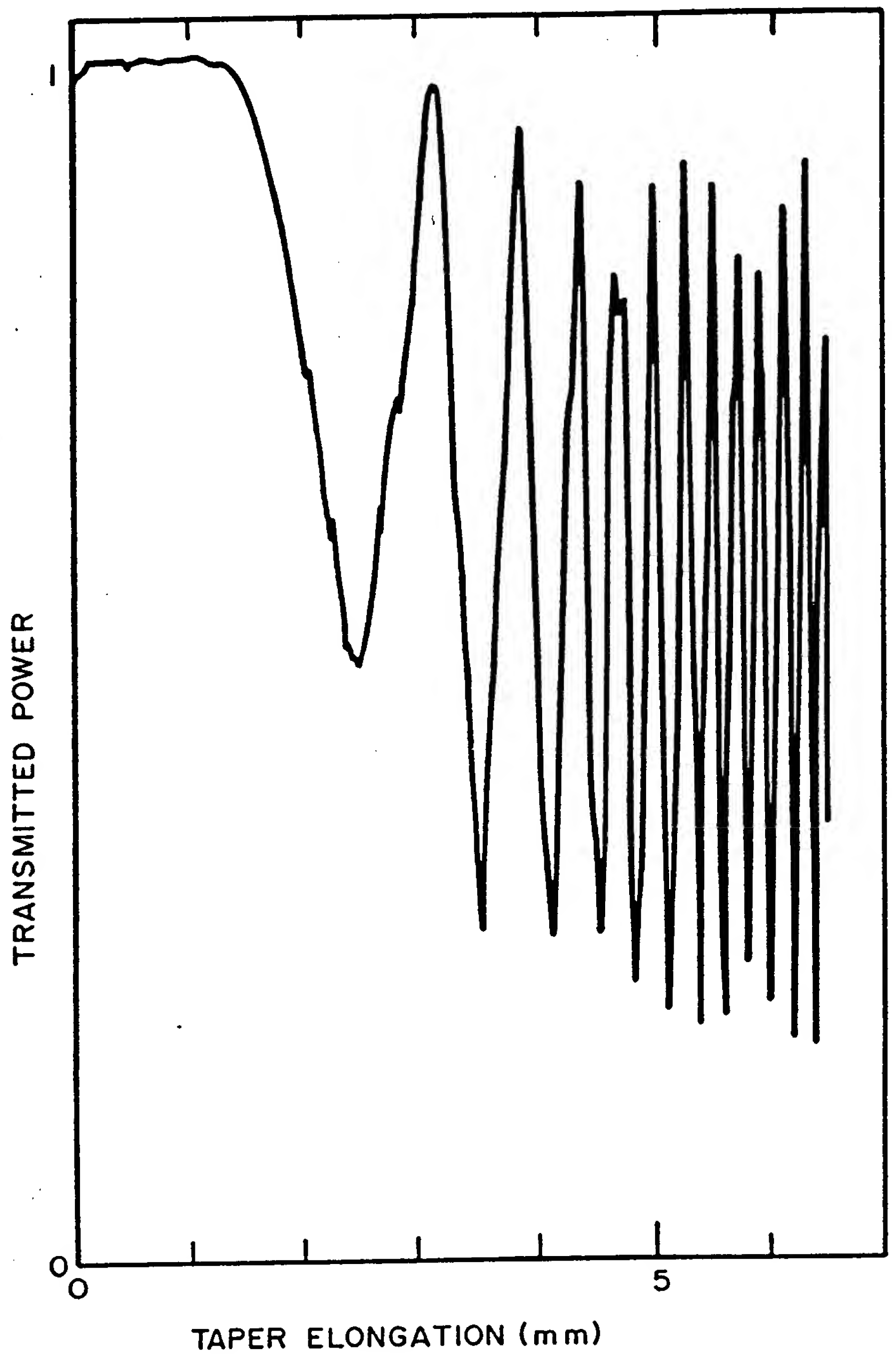

FIG. 3

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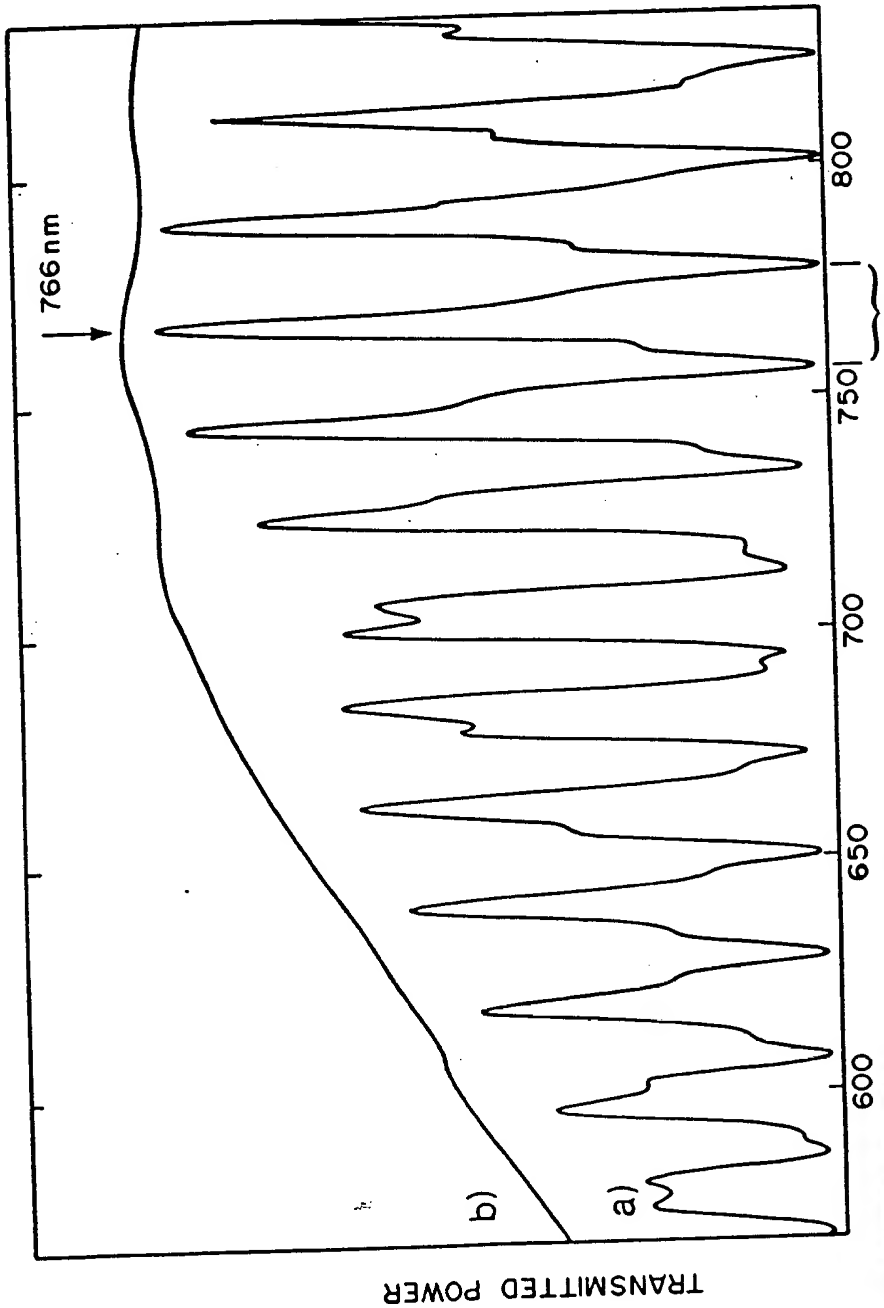

FIG. 4

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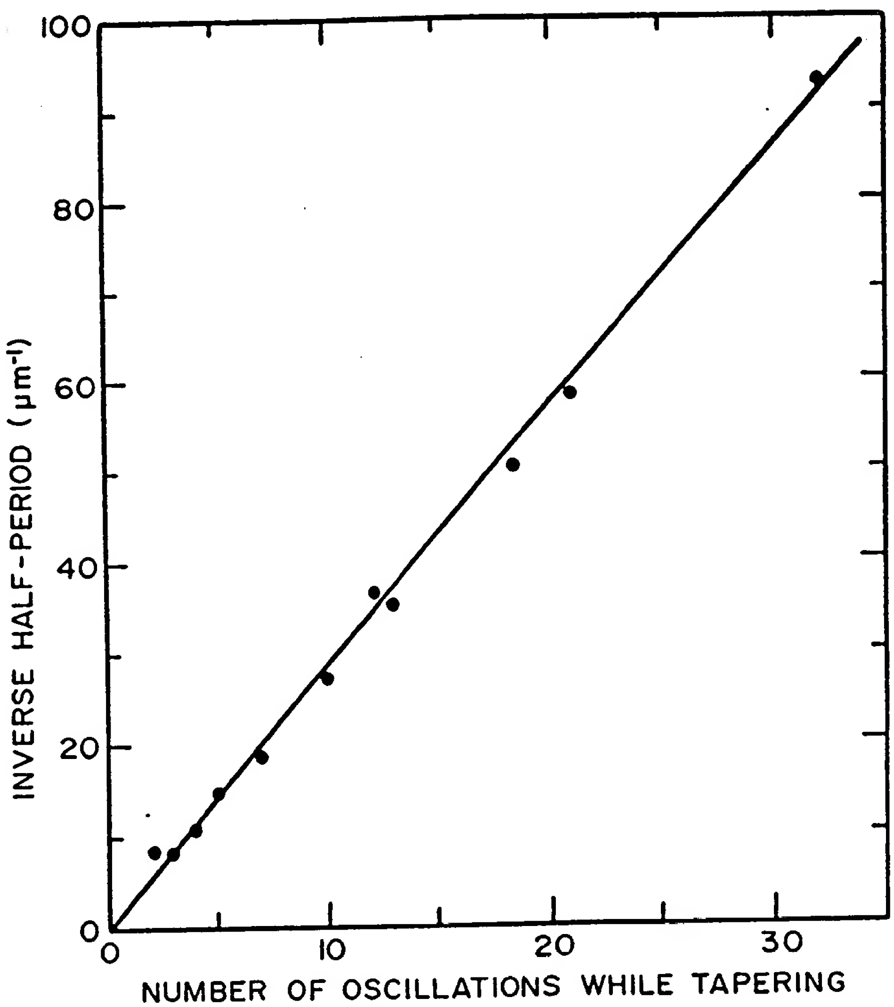

FIG. 5

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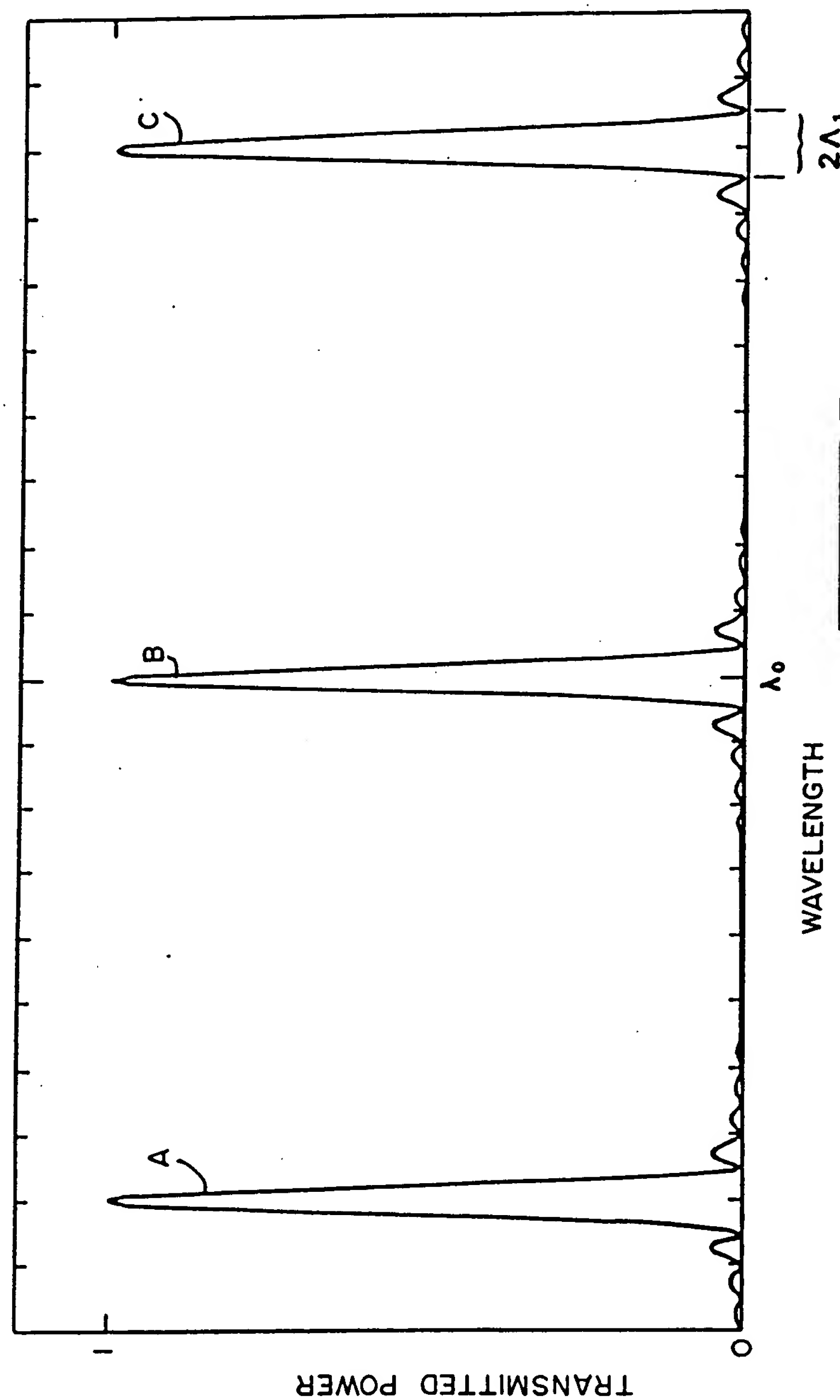

FIG. 6

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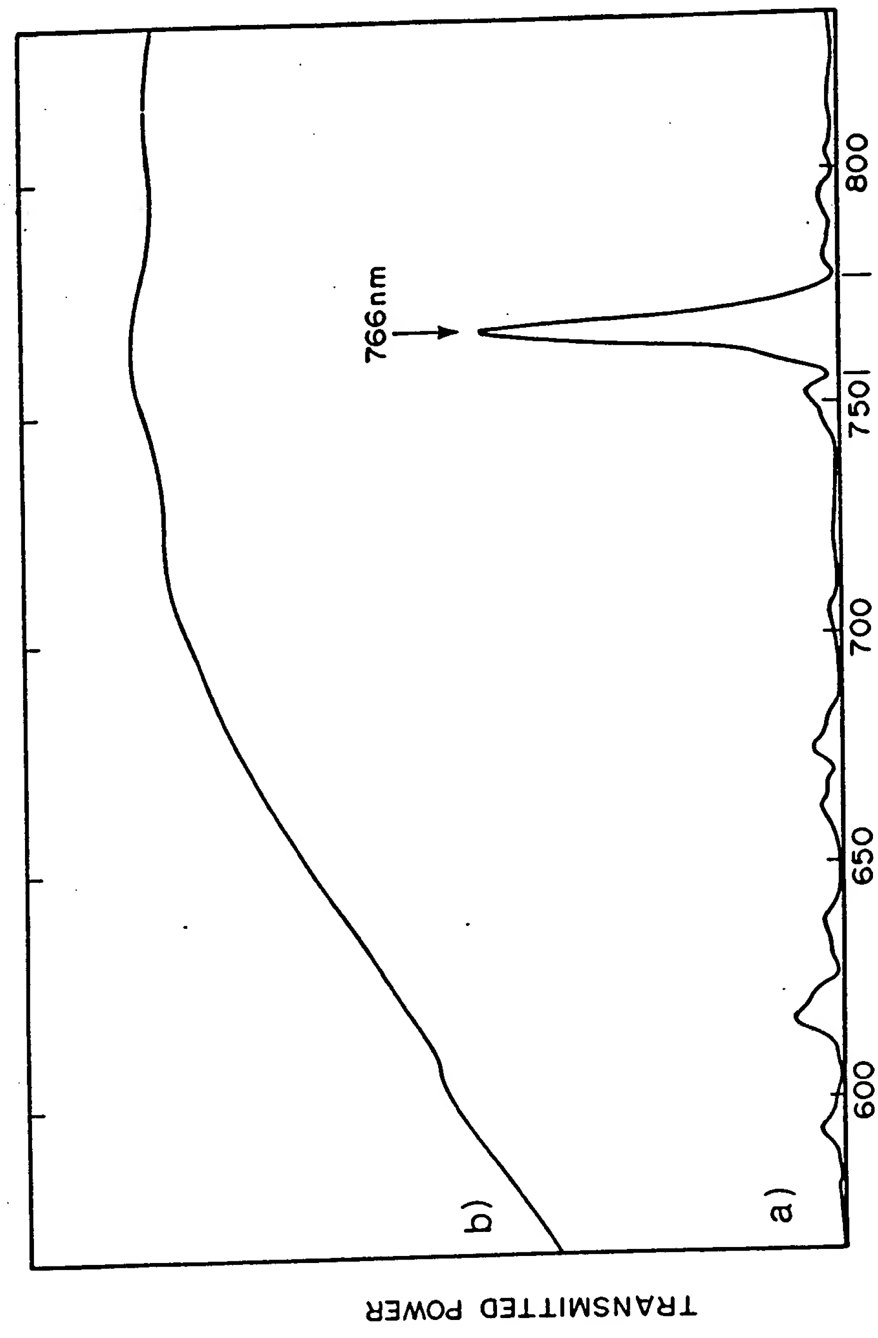
766nm
$2\Delta\lambda$
600
650
700
750
800
WAVELENGTH (nm)
TRANSMITTED POWER
a)
b)

FIG. 8

[illegible] & [illegible] Walker

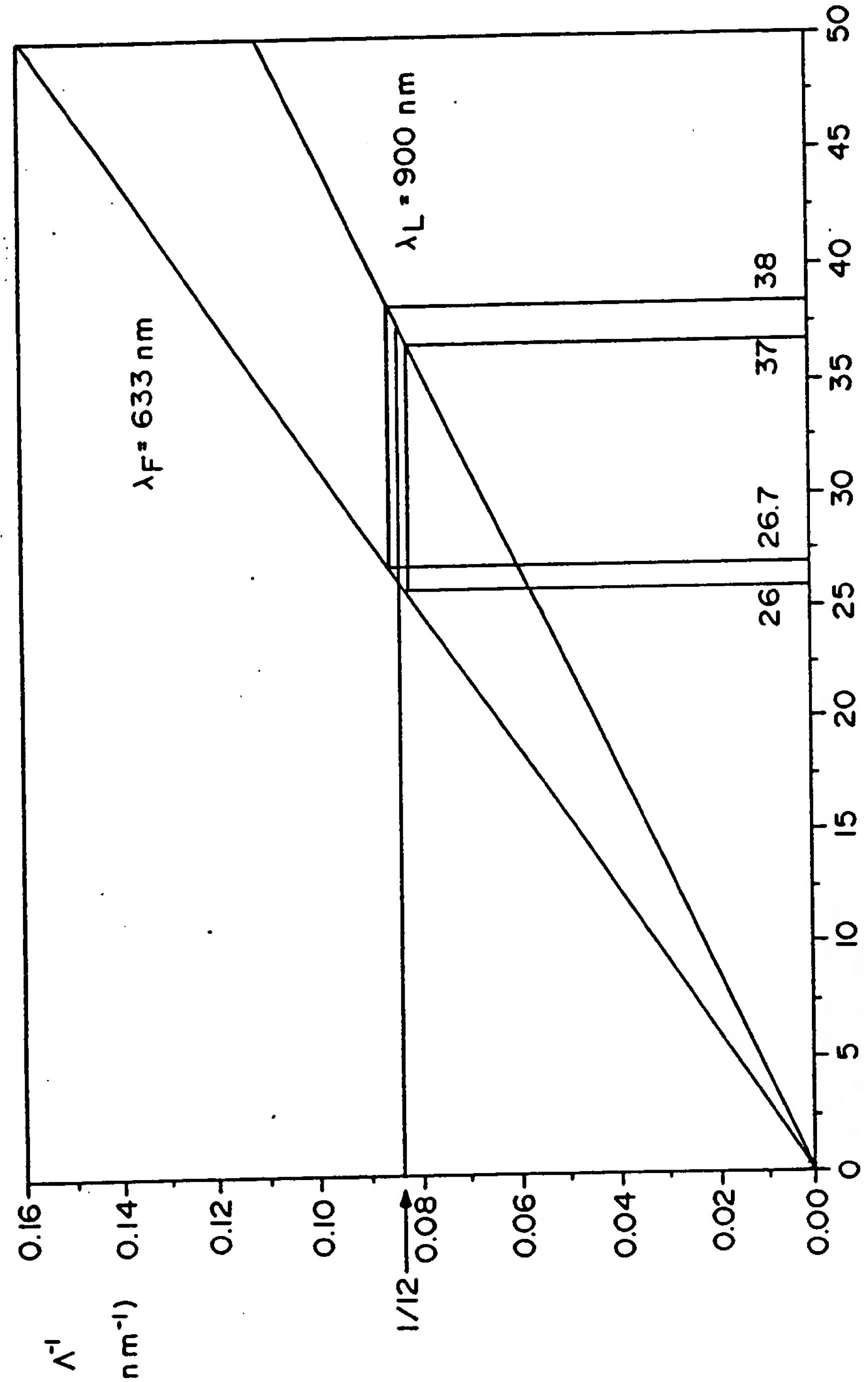

FIG. 9

Goudreau Gage Dubuc & Martineau Walker